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Greenhouse gas emissions of forest bioenergy supply and utilization in Finland

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ABSTRACT

The paper assesses greenhouse gas (GHG) emissions of forest bioenergy supply and utilization in Finland. Each step in the supply chains of harvesting residues (HR), small-diameter energy wood (EW) and stumps (ST) is assessed separately, with geography-related differences between Northern and Southern Finland (NF and SF) taken into consideration. Furthermore, the GHG performance of five distinct bioenergy options—(1) combined heat and power production, (2) condensing power production, (3) torrefied pellets, (4) gasification, and (5) pyrolysis oil production—is assessed and compared with that of current reference systems in Finland and also the European Union (EU) sustainability criteria. If soil carbon stock (SCS) changes and possible storage emissions are omitted, the GHG emissions deriving from the supply chain of comminuted forest biomass to plants are 2.4, 3.0, and 2.6 $gCO_2eq\ MJ^{-1}$ for HR, EW, and ST in SF, respectively. In NF, the corresponding values are 2.9, 3.6, and 3.2 $gCO_2eq\ MJ^{-1}$, respectively. If SCS changes and possible emissions from storage are accounted for, the emissions for HR, EW, and ST are in the ranges 9.2–49.2, 24.4–64.4, and 33.1–73.1 $gCO_2eq\ MJ^{-1}$ in SF and 12.7–52.7, 29.4–69.4, and 39.5–79.5 $gCO_2eq\ MJ^{-1}$ in NF. Most supply-chain GHG emissions arise from SCS changes and possible emissions from storage of comminuted biomass, both of which may involve significant uncertainty factors. In comparison to local reference systems, significant GHG savings can be achieved through energy utilization of forest biomass, but if SCS changes and, in particular, storage emissions are taken into account, fulfillment of the EU sustainability criteria is not guaranteed.

Contents

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1. Introduction

Energy produced by combustion of biomass-based fuels is considered carbon-neutral [1]. For biomass from forests, the presumption is that, as long as the harvested areas grow back as forests, the carbon dioxide (CO_2) emitted will be recaptured in the growing trees over time [2]. However, in addition to the assumed forest re-growth, which should in time neutralize the CO_2 emissions released in combustion, there are several other steps in the process that have to be taken into account and various aspects to be considered when one is assessing the greenhouse gas (GHG) performance of bioenergy systems.

Life-cycle assessment (LCA), as a methodology, involves evaluation of all relevant process steps and environmental burdens associated with a given system, producing results that may be used in development of the system itself but that also should facilitate objective comparison between systems. Life-cycle assessment is the method chosen by the European Union (EU) for bioenergy sustainability assessments [3,4]. However, the results of LCA depend on input parameter values, system boundaries, allocation procedures, and the fossil reference system, and many key parameters vary with the system and by location [5,6]. Forest biomass from natural forests represents a geographically distributed feedstock, and geographical location affects the results of forest bioenergy LCA in several ways. For example, raw material′s availability, forest operations, transportation possibilities, biomass end use, fossil reference systems, and forest carbon balances are all to some extent dependent on geographical location.

In 2009, the EU Renewable Energy Directive (RED) [3] introduced binding sustainability criteria for liquid biofuels, which will likely also be applied for solid and gaseous biofuels [4]. These requirements include 35% GHG savings in comparison to fossil comparator values, and they will become stricter, reaching a requirement of 50% and 60% savings, respectively, in 2017 and 2018 for new installations. Even though default GHG performance figures for various bioenergy systems and fossil comparator values are presented [3] and [4], the actual savings achieved, if any, vary. Therefore, for determination of whether or not these criteria are met by a given bioenergy system, comprehensive life-cycle GHG performance assessments are needed and indeed have been called for by many researchers [7–10].

The objectives of this paper are (1) to assess and summarize the GHG emissions derived from forest biomass supply chains in Finland and (2) to assess the net reductions in GHG emissions achieved via various forest biomass energy utilization systems relative to both the current situation in Finland and the EU′s sustainability criteria. In the emission calculations of this study, sources and data that the authors assessed as representing Finnish conditions as realistically as possible were used. Also, previous relevant studies addressing the three most significant sources of possible GHG emissions are reviewed: soil carbon stock changes, emissions due to decay of comminuted forest biomass during storage, and forest fuel supply chains (i.e., emissions related to machinery use in the supply chains).

The categories of forest biomass assessed in this study include harvesting residues from final fellings (HR), spruce (*Picea abies*) stumps from clear-cuts (ST), and small-diameter energy wood from early thinnings or first thinnings (EW).

The results and information presented in this paper can be used in decision-making and further research examining various possibilities for use of forest biomass for energy in Finland as means to reduce GHG emissions, both from a legislative point of view (i.e., in terms of possible GHG savings calculated in line with the EU RED methodology) and from the perspective of the actual GHG savings possible under current conditions in Finland.

2. Materials and methods

When this was possible, emissions dependent on geographical location were assessed separately for Southern Finland (SF) and Northern Finland (NF) [11] (Fig. 1). The boundaries applied in the study are presented in (Fig. 2) and the feedstock properties in (Table 1).

2.1. Time horizon

In this study, the emissions were assessed in terms of global warming potential (GWP) on a 100-year time horizon (TH). The GWP value can be used for estimating the potential future climate impact of different gases in a relative sense [15], and it is the basis of, for example, the Kyoto Protocol, the EU RED, and the US Renewable Fuel Standard for long-term emissions [16–18]. Also, a 100-year TH can be considered appropriate for forest bioenergy assessments in Nordic conditions, since harvested forests can be assumed to re-grow completely in 100 years [19–21]. The GHG emissions are given as CO_2 equivalents (CO_2eq).

2.2. GHG emission assessment—EU RED methodology

The steps presented by the EC for bioenergy life-cycle GHG emission assessments were followed in the work reported upon here [3,4]. Forest bioenergy supply in Finland is based on “Forest Land Remaining Forest Land” [22], meaning that there is neither direct nor indirect associated land-use change. It was also assumed that the removal of forest biomass follows sustainable forest-management practices [23] and that future forest growth is not affected. Furthermore, on a nationwide scale, the current annual growth of forests in Finland also clearly exceeds the amount felled, resulting in a net increment of wood volume and carbon stocks in living wood. This trend is expected to continue [11]. Therefore, the emissions related to carbon-stock changes caused by land-use change were assumed to be zero. Also, emission savings from soil carbon accumulation via improved agricultural management, carbon capture, and geological storage or replacement, and from excess electricity generation from co-generation for liquid biofuels, are not relevant for the bioenergy systems addressed in this paper. Accordingly, the EU RED calculation procedure for forest bioenergy is as follows:

$$E = e_{ec} + e_p + e_{td} + e_u$$

where E = for liquid biofuels, total emissions from the use of the fuel; for solid and gaseous biofuels, total emissions from the production of the fuel before energy conversion, e_{ec} = emissions from the extraction or cultivation of raw materials, e_p = emissions from processing, e_{td} = emissions from transportation and distribution, e_u = emissions from the fuel in use.



Fig. 1. Finland is divided into Southern and Northern Finland for the supply-chain GHG assessment.

The steps along the bioenergy production and use chains addressed in this paper are described in subsections 2.3–2.6, and the emissions are summarized in (Table 4).

2.3. Forest biomass supply chains

2.3.1. Emissions from extraction or cultivation of raw materials (e_{ec})

2.3.1.1. Cultivation. HR and ST are byproducts of final fellings and EW is harvested during forest thinning. All of these operations aim to produce higher-value material—i.e., saw or veneer logs and pulpwood. Therefore, in this paper, only additional operations needed for utilization of HR, ST, or EW as energy were accounted for. This boundary for the study is in line with EC recommendations [3,24] and with several other studies in which forest bioenergy GHG balances are assessed—e.g., [25–28].

2.3.1.2. Fertilization. Removal of forest biomass can cause nutrient loss, which can be compensated for through fertilization. In [29,30] the emissions resulting from compensation for nutrient loss via fertilization and recirculation of ash were found to be in the 0–1.9 g CO_2eq MJ^{-1} range. However, currently only 0.24% of Finnish forest area is fertilized in any given year [11]; therefore, in a 100-year rotation period, 76% forests remain unfertilized. Furthermore, fertilization should be considered as a way to increase forest productivity, for obtaining more economic profit from saw or veneer logs and pulpwood [31], and if good forest-management practices are followed, fertilization is not generally recommend as a means of offsetting nutrient loss due to collection of biomass for energy use [23]. Therefore, in this paper, GHG emissions due to forest fertilization or ash recirculation are not included in the basic scenario. They are, however, included as optional emissions, for which a value in the center of the range presented above is assumed [29,30].

2.3.1.3. Extraction. Because HR (branches and tree tops) are byproducts of final fellings, the only additional operation at the harvesting site is forwarding to the roadside by a forwarder. In contrast, ST must be lifted and sheared, and EW needs to be felled and bunched before forwarding, as follows.

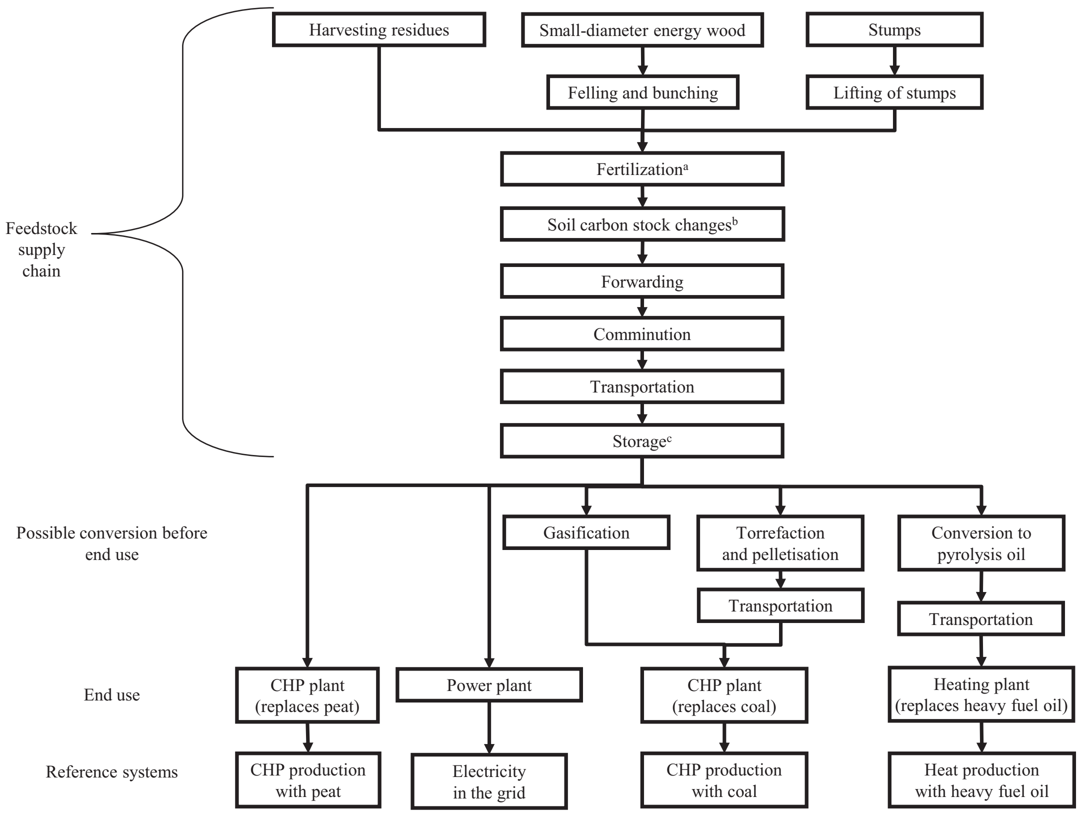
EW felling and bunching: The emission calculations for EW felling and bunching per operating hour were based on cost and productivity studies presented in [32–34] for a multi-stem harvester. Fuel consumption was based on [35]. The EW harvesting conditions, representing typical harvesting sites in NF and SF, were based on National Forest Inventories [36].

ST lifting: The emission calculations for ST lifting assumed an excavator equipped with a stump-lifting device, which shears the ST during extraction and places them in a heap at the site [37]. The per-operating-hour productivity of stump lifting was based on [37,38] and the fuel-consumption figures on [35]. The ST lifting conditions represented typical sites in NF and SF [39].

2.3.1.4. Forwarding. For us to provide a comprehensive assessment of the GHG emissions related to forest biomass supply for energy purposes in Finland, a Geographical Information System (GIS) assessment of forwarding distances was conducted. This was done because there were no suitable published results or data available that are representative of the whole geographical area in question (the entirety of Finland). The GIS assessment was conducted as follows: First, the geographical reference area (again, Finland) was classified in terms of its status as productive forest land, to a resolution of 1 ha. The classification was based on the Finnish Forest Research Institute's definition of forest land [40] and on land-use data provided by the National Land Survey of Finland [41]. Areas with restricted use were excluded [42]. Then, direct distances from the midpoints of each 1 ha square of forest land to the nearest suitable road were calculated. These direct distances were multiplied by a factor of 1.4 to yield the actual distances covered by the forwarder [43]. Highways were excluded from the assessment, since they are not suitable for roadside operations of forest biomass supply [43]. The amount of biomass at each land midpoint was based on data provided by the Finnish Forest Research Institute. The method of allocating biomass to the land points is presented in [44,45], and the potential-calculation methods are presented in [37,46]. The average (energy-content-weighted) forwarding distances were 470 and 214 m in NF and SF, respectively. Previous studies have presented forwarding distances ranging from approximately 200 to 300 m [47–50]. The difference between the values stated in previous studies and the distances calculated in the present study arise from the fact that the values presented previously were based on actual logging or energy-wood harvest sites and represent only one part of the country or certain areas, while the average distances calculated in our study represent all forest land with potential as area for biomass supply in Finland.

GHG emissions of forwarding:

HR: The emission calculations for HR forwarding were based on the time consumption presented in [51], per-operating-hour productivity presented in [52], and fuel consumption presented in



[a] In this study, fertilization is accounted for as an optional stage. See section 2.3.1 for details.
[b] GHG emissions due to soil carbon stock changes are not accounted for in the basic scenario of this study, because they are not taken into account in the EU RED methodology, they are, however, accounted for as optional emissions. See section 2.4 for details.
[c] In this study, GHG emissions due to storage of comminuted forest biomass are accounted for as optional emissions. See section 2.3.3 for details.

Fig. 2. Study boundaries.

Table 1
The properties of comminuted harvesting residues (HR), stumps (ST), and small-diameter energy wood (EW)

	Heating value (GJ m_{solid}^{-3})	Moisture content (%)	Density, dry (kg $m_{solid,\ dry\ matter}^{-3}$)	Density, wet (kg $m_{solid,\ wet\ matter}^{-3}$)
Harvesting residues (HR)	7.49[a]	47[a]	425[b]	802
Stumps (ST)	7.67[a]	37[a]	435[b]	690
Small-diameter energy wood (EW)	7.63[c]	36[c]	420[c]	656

[a] [12].
[b] [13].
[c] [14].

[35]. The load volume in HR forwarding was 7.8 m_{solid}^3 [52]. The conditions represented typical harvesting sites in NF and SF [39].
EW: The emission calculations for EW forwarding were based on productivity per operating hour as presented in [53,32,33]. The load volume in EW forwarding was 6.0 m_{solid}^3 [32,33]. The fuel consumption assumed for a forwarder was based on [35].
ST: After lifting, the stumps are forwarded to the roadside with a forwarder. The emissions calculations for ST forwarding were based on the load volume (8.6 m_{solid}^3) and per-operating-hour productivity presented in [41,54] and fuel-consumption data presented in [35].

2.3.2. Emissions from processing (e_p)

For HR, ST, and EW, the only processing step needed before combustion or conversion to another form is comminution—i.e., chipping or crushing. In this paper, possible drying of feedstock before conversion was accounted for in the conversion efficiencies. The emissions calculations were based on the most common comminution methods in Finland. For HR and EW, the dominant method is roadside chipping with mobile chippers, and the dominant method for ST is crushing with a mobile crusher at the plant or at terminal sites [55,56]. The figure for the fuel consumption of a mobile chipper (including loading) is based on [57], and that for a mobile stump-crusher is based on the fuel consumption of crushing presented in [58] and the fuel consumption of loading presented in [57].

2.3.3. Emissions from transportation and distribution (e_{td})

2.3.3.1. Transportation. The emissions derived from long-distance transportation of biomass feedstock in Nordic conditions have generally been assessed to be low in comparison to the possible GHG savings achieved through replacement of fossil fuels [59–62,44,45,28],. On the other hand, transportation emissions per unit of energy delivered to the plant grow as the amounts delivered

increase and the distances grow [44,45,59,28]. In GIS-based assessments for Finnish conditions, the GHG emissions derived from transportation of forest biomass by truck from roadside storages to end-user locations have been estimated to range from 0.43 to 1.76 and 0.56 to 2.46 $gCO_2eq\ MJ^{-1}$ in SF and NF, respectively, depending on the amount transported (from 0.36 to 7.2 $PJ\ yr^{-1}$), biomass availability, and road-network properties [61,44,45].

2.3.3.2. Storage. After comminution, forest biomass storage piles start decaying and emitting CH_4 and N_2O. Literature and data sources regarding GHG emissions (specifically, CH_4 and N_2O) of comminuted forest biomass stockpiles are scarce. Previous studies addressing the GHG emissions from storage of comminuted woody biomass (forest biomass, bark residues, or sawdust) are presented in (Table 2).

Emissions due to biomass storage depend on many factors, among them moisture content (MC), prevailing weather conditions, and particle size [63–66]. Furthermore, if the storage period for comminuted biomass is kept short, the dry-matter losses and emissions can be estimated to be negligible [63,67]. This storage option is sensible also from an economic standpoint, since prolonged storage and decay of material also lead to energy losses. Furthermore, storage emissions are not accounted for in the EU RED default values [68], so the possible emissions from storage are included for purposes of this paper only as optional emissions and presented as a range of emissions that may result from six-month storage of comminuted feedstock. In this range of possible emissions, values are given for feedstock with 40 and 60% MC, resulting in emissions of 16 and 40 $gCO_2eq\ MJ^{-1}$, respectively, consistent with values presented in [63] for HR. In the GHG emission calculations of the present paper, GHG emission values based on [63] were used, because they were assumed to represent the conditions of forest biomass supply in Finland most realistically. The MC figures for HR, EW, and ST in this study range from 36 to 47% (see Table 1); therefore, the storage emission value for feedstock with a 40% MC can be assumed to represent the supply situations assessed in this study more realistically than can the value given for feedstock with a 60% MC. However, because the MC of

Table 2
Studies addressing the GHG emissions from storage of comminuted woody biomass.

Study	Type of material	Location	Description/methods	GHG emissions
Wihersaari [63]	[a]Forest residues	Finland	Estimation is based on degradation of biogenic material in composting and properties of forest residues. Gases: CH_4 and N_2O	16 $gCO_2eq\ MJ^{-1}$, for material with 40% moisture content 40 $gCO_2eq\ MJ^{-1}$, for material with 60% moisture content. Duration of storage: 6 months
Wihersaari and Palosuo [64]	[a]Forest residues	Finland	"conservative" theoretical estimation based on possible material losses during storage and biowaste composting studies Gases: CH_4 and N_2O	11 $gCO_2eq\ MJ^{-1}$, Duration of storage: 6 months
BTG biomass technology group BV [65]	Woodwaste (mainly bark)	Bulgaria	Two woodwaste stockpiles (areas 15,000–28,000 m^2, 8–10 m height), on-site measurements and a landfill gas calculation model. Gases: only CH_4	[b]9.3–11.7 $gCO_2eq\ MJ^{-1}$, for new material added into an existing old storage pile. Duration of storage: 1 year
Pier and Kelly [66]	Sawdust	Tennessee, USA	Measurements from eight sawdust piles (~10 m height). Gases: CH_4	138–170 $gCO_2eq\ MJ^{-1}$, for 80–100% degradation of organic matter. Duration of storage: unlimited

[a] Forest residues = harvesting residues (HR) in this current study.
[b] In [65], results are given in $m^3_{CH4}\ kg_{dry\ biomass}{}^{-1}$. Conversion to $gCO_2eq\ MJ^{-1}$is based on 16.04 g $mol_{CH4}{}^{-1}$, 0.0224 $m^3\ mol^{-1}$ and properties of biomass presented in (Table 1).

Table 3
Soil carbon stock assessments regarding forest biomass energy use relevant to Finnish and Nordic conditions. HR harvesting residues; EW small-diameter energy wood; ST stumps. SF Southern Finland; NF Northern Finland.

Study	Location	Type of forest biomass (diameter, if specified)	Soil carbon model	Proportion of undecayed material left after 100 years of natural decay in the forest	GHG emissions calculated for a single event combustion, TH 100 years ($gCO_2eq\ MJ^{-1}$)
Repo et al. [62]	Southern Finland and Northern Finland	HR (2 cm), EW (10 cm), ST (30 cm)	Yasso07 [70]	SF: HR 4.9%; EW 20.0%, ST 28.5% NF: HR 8.5%; EW 24.3%; ST:34.0%	[a]HR; NF, SF: 8.8, 5.9 EW; NF, SF: 24.8, 20.4 ST; NF, SF: 35.4, 29.6
Repo et al. [71]	Southern Finland	HR (2 cm), ST (26 cm)	Yasso07 [70]	HR~ 5%; ST ~25%	[a]HR: ~6 ST: ~26
Kujanpää et al. [72]	Southern Finland	HR	Yasso (older version) [73]	5%	[c]HR: 6
Palosuo et al. [29]	Finland	HR	unspecified "dynamic model"	3%	[a]3.1
Sathre and Gustavsson [27]	Northern Sweden	HR, EW, ST	A decay function and decay constants for HR, EW and ST are given	[b]HR 0.1%; EW 3.7%, ST 1.0%	[b]HR: 0.1 EW: 3.7 ST:1.0
Zetterberg and Chen [74]	Southern Sweden	HR, ST	Q-model [75]	Decay rates not specified separately	HR: 2.0 ST 3.0
Lindholm et al. [76]	Southern Sweden and Northern Sweden	HR, ST	Q-model [75]	Not given (TH 20 years)	Not given (TH 20 years)
Eriksson et al. [77]	Central Sweden	HR, ST	Q-model [75]	Not given, (TH 273–291 years)	Not given, (TH 273–291 years)

[a] Calculated by the authors of this paper, based on decay rates presented in the original publication.
[b] Proportion of material left after 100 years and the corresponding GHG emissions were calculated by the authors of this study using the decay function and decay constants presented in [27]. The decay constants used in [27] were derived from [78–80].

Table 4
The unit-process descriptions, key parameters, and resulting GHG emission values used in the emission calculations (NF=Northern Finland, SF=Southern Finland).

Phase	Description of unit process and key parameters	GHG emissions
Emissions included in the basic scenario		
Production and supply of diesel fuel used	Diesel mix at refinery (5.75% bio-components), EU-27 [107]	320 $gCO_2eq\ kg_{diesel}^{-1}$
in machines ST lifting	Lifting of stumps with an excavator [35,37–39]	NF: 0.78 $gCO_2eq\ MJ^{-1}$ SF: 0.66 $gCO_2eq\ MJ^{-1}$
EW harvesting	Multi-stem harvester [32–36],	NF: 0.66 $gCO_2eq\ MJ^{-1}$ SF: 0.65 $gCO_2eq\ MJ^{-1}$
Forwarding	Forwarder load volumes HR, EW, ST: 7.8, 6.0, 8.6 m^3_{solid} [32, [33,35,39,51–54] Forwarding distances SF, NF: 214, 470 m[a]	HR – SF, NF: 0.36, 0.49 $gCO_2eq\ MJ^{-1}$ EW – SF, NF: 0.35, 0.52 $gCO_2eq\ MJ^{-1}$ ST – SF, NF: 0.29, 0.39 $gCO_2eq\ MJ^{-1}$
Comminution	HR, EW: Mobile drum chipper [57] ST: Mobile stump-crusher [68,58]	HR, EW: 0.91 $gCO_2eq\ MJ^{-1}$ ST: 0.50 $gCO_2eq\ MJ^{-1}$
Transportation from roadside to plant	Truck (60 t), incl. loading and unloading operations Payloads – HR, EW, ST: 33.8, 27.7, 16.7 t	NF: 1.51 $gCO_2eq\ MJ^{-1}$, SF: 1.1 $gCO_2eq\ MJ^{-1}$ [61,44,45]
Gasification	Net conversion efficiency: 98% [89], [101]	[b]
Pyrolysis-oil production	Net conversion efficiency: 89% [103]	[b]
Torrefaction and pellet production	Net conversion efficiency: 76% [95-99]	[b]
Condensing-power production	Net electricity-production efficiency 40% [104]	[b]
Combustion of biomass at CHP plant in fluidized bed boiler	CH_4 and N_2O, fluidized-bed boiler	1.5 $gCO_2eq\ MJ^{-1}$ [84]
Transportation of pyrolysis oil/torrefied pellets	Truck (60 t, total capacity, payload 40 t, empty returns) [108] Distances: Pyrolysis oil 440 km, torrefied pellets 230 km	Pyrolysis oil: 1.4 $gCO_2eq\ MJ^{-1}$ Torrefied pellets: 0.6 $gCO_2eq\ MJ^{-1}$
Optional emissions (not included in the basic scenario)		
Storage	Comminuted material (40% MC and 60% MC) in a pile outdoors for 6 months	0–40.0 $gCO_2eq\ MJ^{-1}$[63]
Soil carbon stock changes	Decrease of soil carbon stock on a 100-year TH[c] [62]	HR; NF, SF: 8.8, 5.1 $gCO_2eq\ MJ^{-1}$ EW; NF, SF: 24.5, 20.2 $gCO_2eq\ MJ^{-1}$ ST; NF, SF: 35.3, 29.6 $gCO_2eq\ MJ^{-1}$
Fertilization	Nutrient compensation via fertilization and ash recirculation	0.95 $gCO_2eq\ MJ^{-1}$ [29,30]
Combustion of torrefied biomass at a coal CHP plant, non-CO_2 GHGs	CH_4 and N_2O	0.6 $gCO_2eq\ MJ^{-1}$ [85]
Combustion of ground biomass at a condensing power plant, non-CO_2 GHGs	CH_4 and N_2O	0.6 $gCO_2eq\ MJ^{-1}$ [85]
Combustion of pyrolysis oil at a heating plant, non-CO_2 GHGs	CH_4 and N_2O	0.4 $gCO_2eq\ MJ^{-1}$ [85]
Combustion of gasified biomass at a coal CHP plant, non-CO_2 GHGs	CH_4 and N_2O	0.4 $gCO_2eq\ MJ^{-1}$ [85]
Emissions of reference systems in Finland		
Peat supply and combustion	Average production emissions (incl. field, stockpile, and machine use) and combustion in a fluidized-bed boiler [109]	116.8 $gCO_2eq\ MJ_{fuel}^{-1}$
Hard-coal supply and combustion	Hard-coal mix at plant (EU-27) and combustion [110,111]	105.0 $gCO_2eq\ MJ_{fuel}^{-1}$
Heavy-fuel-oil supply and combustion	Heavy fuel oil at refinery (EU-27) and combustion [112,113]	89.5 $gCO_2eq\ MJ_{fuel}^{-1}$
Electricity production	Hydropower[114] Average electricity, Finland [115] Average electricity, EU-27[116] Coal power [117]	3.9 $gCO_2eq\ MJ_{electricity}^{-1}$ 99.2 $gCO_2eq\ MJ_{electricity}^{-1}$ 135.0 $gCO_2eq\ MJ_{electricity}^{-1}$ 252.0 $gCO_2eq\ MJ_{electricity}^{-1}$

[a] See Section 2.3.1.4 for details on forwarding distance assessment.
[b] The emissions of the biomass supply chain were divided by the net efficiency to obtain the emissions for 1 MJ of product gas/torrefied pellets/pyrolysis oil/electricity.
[c] See Section 2.4 for details on soil carbon stock change calculations.

comminuted feedstock tends to increase when it is stored in a pile outdoors [69], the value representing feedstock with 60% MC was included too, as the upper limit of the possible emission range.

2.4. Soil carbon stocks

When biomass is removed from the forests to be utilized as energy, the amount of carbon input to the soil and litter is decreased. If dead biomass is left in the forest, it decomposes over time and the carbon contained in it is slowly released into the atmosphere. A certain percentage of the carbon contained in the biomass is, however, transformed into humus and soil carbon. Also, when biomass is burned for energy, the carbon content is released immediately instead of over many years or decades as during a natural decay process. The climate impact of these soil carbon stock (SCS) changes depends on the TH on which the impact is assessed and the decay rates of the dead biomass left in the forest.

In this paper, the approach used in the assessment of GHG emissions due to SCS losses represents single-event combustion and a 100-year TH. In other words, the approach involves assessment of the difference in GHG emissions between a scenario wherein the forest biomass fractions (HR, EW, and ST) are used for energy and one in which they are left on the forest floor for 100 years to decay naturally. Time-dependent SCS changes due to collection of forest biomass for energy use in Nordic conditions have been assessed in several studies (Table 3).

The GHG emission calculations performed by the authors of this paper assumed 50% carbon content of dry wood [81,67], and a factor of 3.664 was used for yielding the CO_2 emissions from the carbon content of wood [3].

Because SCS changes are not currently accounted for in EU legislation or EC recommendations [68,3,4], they were not included in the basic scenario of this study. However, for provision of comprehensive emission assessment on a 100-year TH, the SCS changes were included as optional emissions. For this purpose, the

forest biomass decay rates presented by Repo et al. [62] were used, because these are the most recent available, cover NF and SF separately, and include all three forest biomass fractions considered in this study (HR, EW, and ST). Results produced with the Yasso07 soil carbon model [70], used by Repo et al. [62], have also been found to correspond to empirical data [82]. Also, sensitivity analysis (with 50% higher and 50% lower SCS-change-related emissions) was performed for the potential GHG emission savings that may be reached through the various bioenergy schemes of this paper, relative to the EU fossil comparator values.

2.5. Emissions from the fuel in use (e_u)

According to the EC [3,4], the CO_2 emissions of biomass based fuels in use are zero, corresponding also to the UNFCCC accounting scheme [1]. However, even if the biogenic CO_2 emitted in combustion is considered to be zero over time, CH_4 and N_2O may be emitted in addition. The quantities of these non-CO_2 GHG emissions depend on fuel type, combustion technology, operating conditions, control technology, quality of maintenance, and equipment age; accordingly, general-level default values feature significant uncertainties [83,84]. In this paper, for wood chips replacing peat in combined heat and power production (CHP), with fluidized-bed boilers, emission factors presented in [84] were used, which correspond to country-specific emission factors [85]. In the basic scenario for the other bioenergy systems considered in this paper, it was assumed that, because of the higher combustion temperatures and well-controlled furnaces, CH_4 and N_2O emissions are negligible [84,86]. The non-CO_2 GHG emissions were, however, included as optional emissions for the other bioenergy systems, with values presented in [85] used.

2.6. Forest biomass end use and fossil reference systems

Biomass is a limited resource, and competition over the same feedstock is expected to rise; therefore, assessment of optimal biomass use in a given situation is needed if one is to maximize GHG mitigation [25]. The best use of biomass depends not only on the conversion technologies but also on the demand for energy services, supply of biomass resources, and the competition between them [87], so there is no general consensus on what constitutes the best use of biomass.

In this paper, the GHG performance of each of five forest bioenergy systems was compared to fossil reference systems, as suggested in [6]. The bioenergy systems examined in this study represented two traditional and currently used bioenergy systems – CHP and condensing power – and three more recently developed alternatives – pyrolysis, torrefaction, and gasification – which enable replacing fossil fuels with solid biomass in Finland on a commercial scale in the short to medium term (i.e., systems that do not require building of entirely new energy production plants) [88–91].

The fossil reference systems for each of the bioenergy systems were selected to represent the actual current situation in Finland, in the manner described below.

2.6.1. The bioenergy schemes

2.6.1.1. CHP. Combined heat and power production is the most used heating method and the dominant use of solid biomass in Finland [11,92]. For this paper, it was assumed that in the CHP approach (without further conversion of biomass to other energy carriers) comminuted forest biomass replaces peat in a fluidized-bed boiler, which is a typical situation in Finland. Finland has more than 70 CHP plants with a nominal power of 20 to over 300 MW that use peat [93].

2.6.1.2. Torrefied pellets. Torrefied pellets were assumed to be used in a coal CHP plant replacing hard coal. There are coal-fired CHP plants in six cities in Finland, with nominal power values in the range 200–900 MW [94]. Torrefaction is a process in which biomass is roasted in order to improve its fuel characteristics, such as heating value and storability. To improve the energy density and facilitate transportation, torrefied wood can be pelletized. The efficiency of conversion from wood chips to torrefied biomass was assumed to be 82% [95,96]. After torrefaction, the material was assumed to be pelletized, consuming a further 5% of the energy content of torrefied wood [97,98]. Finally, before combustion, grinding of torrefied pellets at the coal plant was estimated to consume a further 2.5% of the energy content of the torrefied wood material when compared to grinding of coal (assuming a conversion rate of 40% from the heating value of fuel to electricity used in the grinding equipment) [95,99]. Therefore, the total efficiency from comminuted biomass to ground fuel ready to be combusted in a coal CHP plant was 76%. The bulk density of torrefied pellets is 750 kg m^{-3} and the heating value is 21 MJ kg^{-1} [100]. At present, there are no industrial-scale torrefaction facilities in Finland, but a torrefied-pellet manufacturing plant with biomass demand of 4.7 PJ is in the planning phase [91]. The pellets were assumed to be produced in Ristiina [91] and used in Helsinki. Transportation of torrefied pellets was included in the emission calculations.

2.6.1.3. Gasification. Gasified biomass was assumed to be combusted in a coal CHP plant replacing hard coal. Gasification is thermal treatment of biomass that results in combustible gaseous products, char, and ash. In this paper, biomass gasification was assumed to be performed in a gasifier connected directly to a coal CHP plant. The net conversion efficiency was 98% [101,90]. There is one biomass gasifier connected to a coal CHP plant in Finland with fuel power of 140 MW [102].

2.6.1.4. Pyrolysis. Pyrolysis oil was assumed to be used in a district heating plant replacing heavy fuel oil. Pyrolysis is thermal treatment of biomass resulting in liquid fuel (pyrolysis oil) and solid and gaseous side products. For this paper, the pyrolysis plant was assumed to be integrated into a CHP plant [90], with a net conversion efficiency of 89% [103]. The heating value of the pyrolysis oil was assumed to be 15.5 MJ kg^{-1}, representing an average heating value for pyrolysis oil made from green harvesting residues and stemwood-derived material [103]. One industrial-scale pyrolysis-oil plant is under construction in Finland [90], with expected biomass demand of 1.6 PJ and planned start-up in fall 2013. Pyrolysis oil was assumed to be produced in Joensuu [90] and used in Helsinki. Transportation of pyrolysis oil was included in the emission calculations.

2.6.1.5. Condensing power. The condensing-power production scheme of this study was based on co-combustion of ground forest biomass with peat in a power plant producing only electricity, with a net electrical efficiency of 40%, including grinding of wood into dust suitable for co-combustion [104]. Currently, there is one forest biomass utilizing condensing-power plant in Finland, using approximately 1.2 PJ of biomass annually [104].

2.6.2. Reference systems in Finland

2.6.2.1. CHP and heat production. Because district heating is produced for local use and the amount of electricity generated in CHP depends on the heat demand, the appropriate reference system produces the same amount of final energy with fossil fuels at the same location. The only difference is the fuel that is

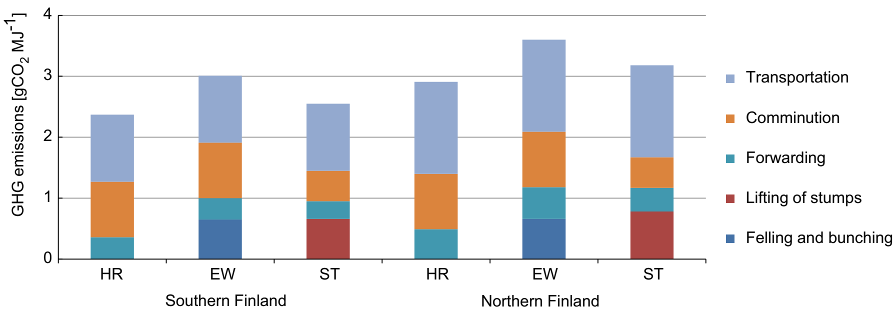


Fig. 3. Supply-chain GHG emissions (basic scenarios); HR = harvesting residues, EW = small-diameter energy wood, ST = stumps.

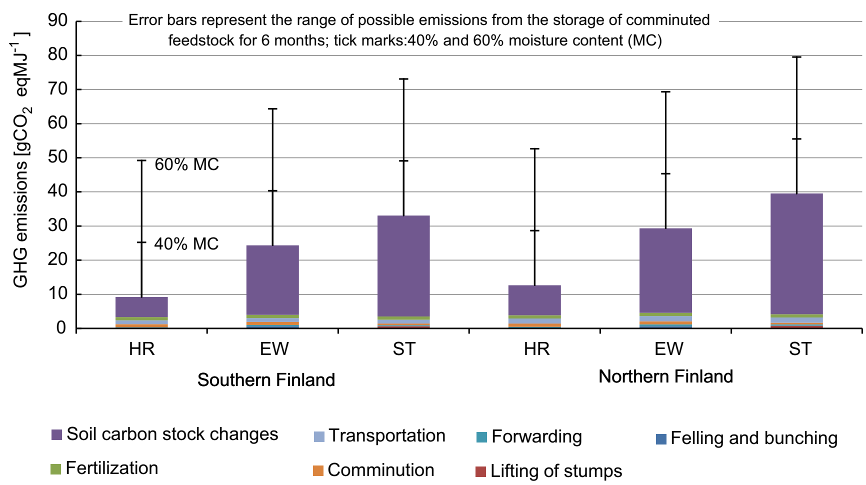


Fig. 4. Supply-chain GHG emissions with optional emissions included. The storage emissions shown represent the emissions possible in six months′ storage of comminuted biomass with 40 and 60% moisture content (MC). HR = harvesting residues, EW = small-diameter energy wood, ST = stumps.

used. Similarly, for production of heat only, the only difference between the bioenergy systems and the fossil reference system is the fuel used. Furthermore, in this paper, the boiler efficiencies were assumed to be the same with biomass based- and fossil fuels.

2.6.2.2. Electricity. Electricity is produced for the Finnish power grid, which belongs to the Nordic electricity market area. The production methods replaced and possible emissions saved through bioenergy utilization can be assessed in several distinct ways, as discussed in [105]. Therefore, to provide a comprehensive analysis, we have assessed hydropower as base power production, average Finnish power, and coal condensing power as marginal power [106]. In addition to these three electricity production types relevant to Finland, we have included average power in the EU-27 countries in the assessment, because the EU RED states that for emissions derived from electricity that is used in processing, average emissions intensity within a "defined region" should be used and in [24] the "defined region" is stated to be the EU. It should be noted that the EU-27 *average power* differs from the EU′ s *fossil comparator* value.

2.6.3. EU fossil comparator values

The EC presents the following fossil reference values for calculation of the GHG emission reductions achieved with bioenergy: 198 $gCO_2eq\ MJ^{-1}_{electricity}$ and 87 $gCO_2eq\ MJ^{-1}_{heat}$ for solid and gaseous biomass, and 77 $gCO_2eq\ MJ^{-1}$ for bioliquids used in heat production [3,4]. Therefore, to facilitate comparison of the bioenergy systems considered in this paper to the EU sustainability criteria, the GHG performance values of CHP, torrefied pellets, gasification, and condensing-power systems were compared against final products – heat and/or electricity – whereas the GHG performance of pyrolysis oil was compared against the reference fuel. Both reference methods have their advantages. When the LCA results for bioenergy systems are given on a per-unit-output basis, the results are independent of the feedstock. This perspective provides an answer to the question of where a given biomass resource should be used. On the other hand, from the perspective of which type of feedstock should be used at a given plant if one is to reduce GHG emissions, LCA results on a per-input basis provide more useful information. To facilitate comparison of the bioenergy systems examined here to the EU comparator values, the thermal end electrical conversion efficiencies of 85 and 25% as presented in [4] were used, and calculation procedures presented in [3,4] were followed.

3. Results

3.1. Supply-chain emissions

The GHG emissions derived from the supply chains of comminuted forest biomass are presented in (Fig. 3) (basic scenarios) and (Fig. 4) (optional emissions included).

In the basic scenarios, the GHG emissions deriving from the supply chain of comminuted forest biomass to plants are 2.4, 3.0, and 2.6 $gCO_2eq\ MJ^{-1}$ for HR, EW, and ST in SF, respectively. In NF, the corresponding basic-scenario values are 2.9, 3.6, and 3.2 $gCO_2eq\ MJ^{-1}$, respectively. If optional emissions are accounted for, the emissions for HR, EW, and ST are in the ranges 9.2–49.2,

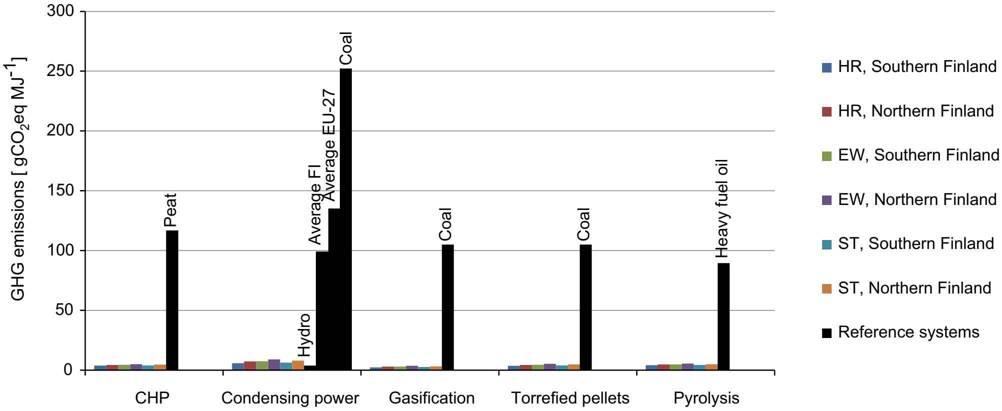


Fig. 5. GHG emissions of the bioenergy schemes (basic scenarios) and their Finnish reference systems′ emissions. Reference systems: for CHP, peat; for condensing power (left to right), hydropower, average power in Finland, average power in the EU-27, and coal power; for gasification, coal; for torrefied pellets, coal; for pyrolysis, heavy fuel oil.

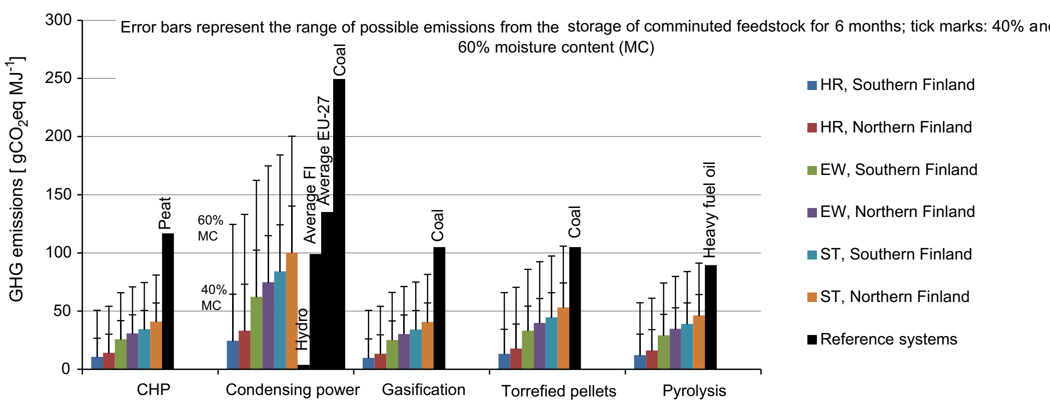


Fig. 6. GHG emissions of the bioenergy schemes (optional emissions included) and their reference systems′ emissions. Reference systems: for CHP, peat; for condensing power (left to right), hydropower, average power in Finland, average power in the EU-27, and coal power; for gasification, coal; for torrefied pellets, coal; for pyrolysis, heavy fuel oil.

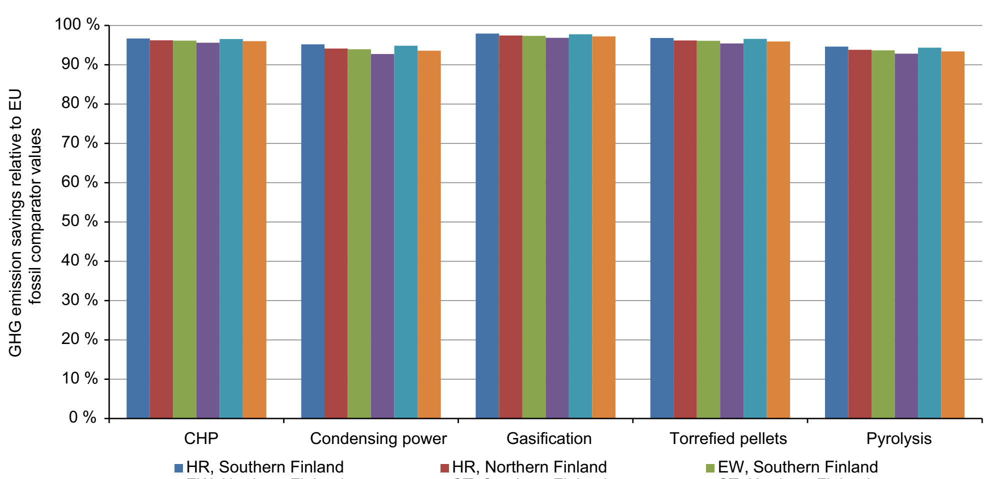


Fig. 7. GHG emission reductions of the bioenergy schemes (basic scenarios, i.e., calculated according to the current EU RED methodology) in relation to their respective EU fossil comparator values. *Note*: The EU sustainability requirement is currently 35% reduction, rising to 60% in 2018.

24.4–64.4, and 33.1–73.1 $gCO_2eq\ MJ^{-1}$ in SF and 12.7–52.7, 29.4–69.4, and 39.5–79.5 $gCO_2eq\ MJ^{-1}$ in NF.

3.2. Emissions of the bioenergy schemes in comparison to reference systems in Finland

The total emissions of bioenergy systems (including the raw-material supply chain, conversion processes, possible transportation to end users, and combustion) and their reference systems in Finland are presented in (Fig. 5) (basic scenarios) and (Fig. 6) (optional emissions included).

CHP: In all scenarios, including when all optional emissions are taken into account, GHG emissions decrease when peat is replaced with forest biomass in CHP production.

Condensing-power production: Condensing-power production with forest biomass increases GHG emissions in all cases relative to hydropower. In the basic scenario, condensing-power production produces lower emissions than average Finnish, average EU-

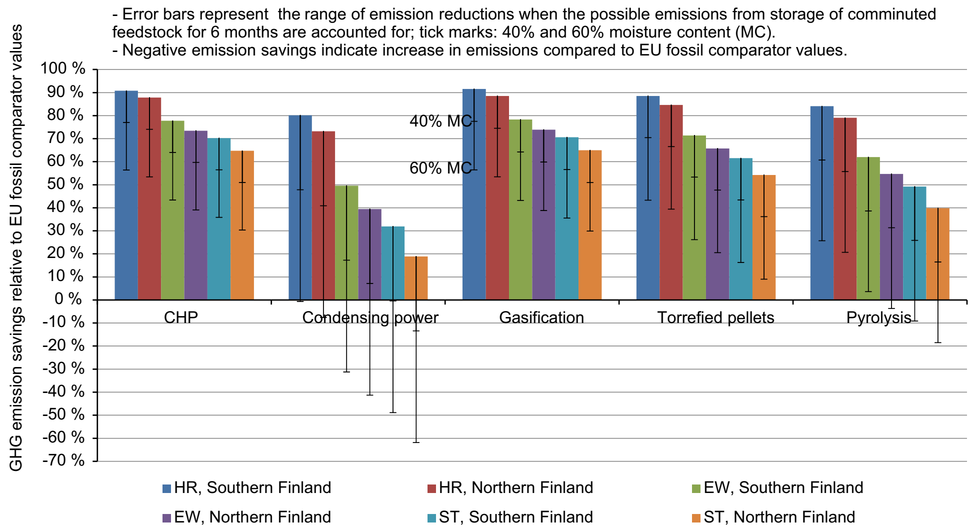


Fig. 8. GHG emission reductions of the bioenergy schemes (optional emissions included) in relation to their respective EU fossil comparator values. *Note*: The EU sustainability requirement is currently 35% reduction, rising to 60% in 2018.

27 or coal power production. If all optional emissions are taken into account, condensing-power production may increase emissions when compared to average Finnish or EU-27 production, depending on the possible emissions released during storage. In comparison to coal power, emissions are reduced in all cases.

Gasification: Replacing coal with gasified forest biomass reduces GHG emissions in all cases, even when all optional emissions are taken into consideration.

Torrefied pellets: Replacing coal with torrefied biomass reduces GHG emissions in all cases, except when ST are used as feedstock in NF and with maximum storage emissions.

Pyrolysis: The GHG emissions are reduced in all pyrolysis-oil cases except when ST are used as feedstock in NF and with maximum storage emissions.

3.3. *Emissions of the bioenergy schemes relative to EU comparator values*

The GHG emission-savings figures for the bioenergy systems relative to the EU fossil comparator values are presented in (Fig. 7) (basic scenarios) and (Fig. 8) (optional emissions included).

In the basic scenarios, all bioenergy systems produce GHG savings of between 93 and 98% when compared to the EU fossil comparator values. When optional emissions are accounted for, GHG emissions ranging from 30 to 91% are achieved if peat is replaced with biomass in CHP production, depending on the storage emissions, if any. In condensing-power, the GHG emission savings possible also depend heavily on the possible storage emissions. Without storage emissions, GHG emission reductions in the 20–81% range can be achieved, but if storage emissions are fully accounted for, the emissions range from 1% reduction to 61% increase. The gasification and torrefied-pellet systems produce GHG savings in all cases, again depending heavily on the storage emissions. The pyrolysis-oil system also produces GHG savings, except if EW in NF or ST in either NF or SF is used as feedstock and potential storage emissions are fully accounted for.

3.3.1. *Sensitivity analysis for GHG emissions due to SCS changes*

The sensitivity of the GHG emission savings relative to the EU fossil comparator values to changes in GHG emissions due to SCS changes is illustrated in (Fig. 9).

As illustrated in (Fig. 9), changes in SCS-related emissions have a significant effect on the potential GHG savings achieved by means of the various forest bioenergy schemes. Of the forest bioenergy schemes considered in this paper, the greatest relative effect of changes in SCS-related emissions is on GHG savings achieved with condensing-power production. This is because with condensing power a relatively large proportion of the fuel′s energy content is lost in the process of conversion from fuel into electricity.

4. Discussion

The results of this paper indicate that

(1) Calculated according to the current EU RED methodology, meaning that SCS changes and possible emissions during storage are omitted,
   - compared to the reference systems in Finland, GHG savings achieved with forest biomass utilization in CHP and heat production range between 94 and 98%. If only electricity is produced, the GHG savings depend on the type of electricity replaced. In general, if hydropower is replaced, emissions increase, but in all other cases emissions decrease.
   - compared to the EU′s fossil comparator values, GHG savings between 93 and 97% are achieved with all of the bioenergy schemes considered in this paper.

(2) If SCS changes and possible fertilization are accounted for on a 100 TH,
   - compared to the reference systems in Finland, GHG savings achieved with forest biomass utilization in CHP and heat production range between 48 and 91%. In this case, condensing power production produces the same emissions as average Finnish power production, or lower.
   - compared to the EU′s fossil comparator values GHG savings of 40–91% are achieved with the CHP and heating schemes, and 20–81% in power production.

(3) If the possible emissions released during six-month storage of comminuted biomass are accounted for (in addition to emissions due to SCS changes and fertilization), the possible GHG saving depend heavily on the storage emissions,
   - compared to the reference systems in Finland, GHG emissions may range from 57% reduction to 2% increase in CHP and heat production,

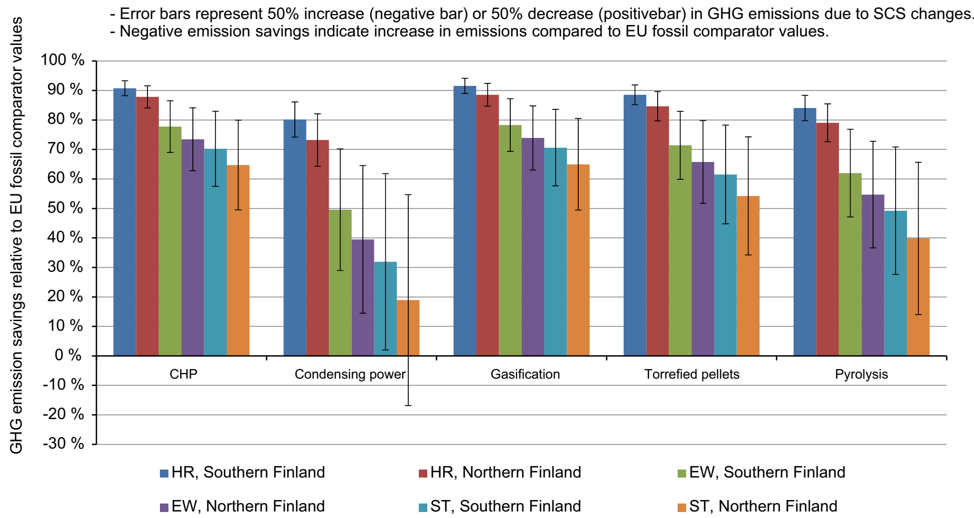


Fig. 9. Sensitivity of the GHG savings relative to EU fossil comparator values to a 50% increase and 50% decrease in GHG emissions due to SCS changes.

Table 5
Previous forest biomass supply chain assessments for Finnish or Nordic conditions. The results presented in this table include only the supply chain emissions, i.e., the results presented in column "Supply chain GHG emissions" do not include GHG emissions due to SCS changes, storage or combustion. HR harvesting residues; EW small-diameter energy wood; ST stumps.

Study	Type of forest biomass	Location	Boundaries of the original study	Supply chain GHG emissions ($gCO_2eq\ MJ^{-1}$)
Lindholm et al. [118]	HR, ST	Southern Sweden for HR Southern Sweden and Northern Sweden for ST	From extraction of forest biomass to comminuted material at end user	[a]HR: ~1.8 Southern Sweden ST: ~2.5 Southern Sweden, ~3.0 Northern Sweden
Kariniemi et al. [119]	HR, EW, ST	Finland	From wood production to comminuted material at end user	[b]HR: 1.8 EW: 2.6 ST: 3.6
Näslund-Eriksson and Gustavsson [120]	HR	Sweden	From extraction of forest biomass to comminuted material at end user	HR: 1.0 EW: 1.5 ST: 1.8
Wihersaari [30]		Finland	From raw extraction of forest biomass to combustion, incl. storage and fertilization.	[c]HR: 1.8

[a] Study [118] included GHG emissions due to production of machines, which were excluded from the emissions presented in this table.
[b] Study [119] presented the emissions per volume of wood, unit conversion was made using the values presented in (Table 1).
[c] For supply chain based on road side chipping of HR.

- the GHG emissions of condensing power production may be higher than the emissions of average Finnish power production, but still lower than those of coal-power production.
- compared to the EU's fossil comparator values, GHG emissions range from 56% reduction to 19% increase in CHP and heat production, while emissions of condensing power range from 1% reduction to 61% increase.

Previous studies concerning forest biomass supply chains in Finnish or comparable Nordic conditions are presented in Table 5.

The relatively large variation in results between previous studies (Table 5) arises from differences in background data and the assumptions made. The corresponding supply chain emissions of this current study (Fig. 3) are higher than the results of previous studies, especially for HR and EW. The difference is mainly due to the emissions of truck transportation, which are assumed to be higher in this current work than in the previous studies. The transportation emission figures used in this study are derived from previous studies by the authors of this current study, in which forest biomass availability and road network properties and current transportation machinery in Finnish conditions were accounted for [45,46,62]. It should also be noted that the transportation emission figure used in this paper represents a central value from case studies in which the transported biomass amounts ranged from a rather limited amount of 0.36 PJ yr^{-1} to a very large demand of 7.2 PJ yr^{-1}. In [118] and [120] the transportation distances have been assumed shorter and the payloads have been assumed to be higher than in the studies on which the value used in this current work are based on. In [30] and [119] transportation equipment and distances have not been specified. It should be noted that the transportation distances and resulting emissions vary considerably between locations.

With respect to feedstock, HR supply produces lower emissions than EW or ST, regardless of location. This is mostly due to the faster natural decay of HR, leading to lower relative SCS losses, but also because of the lower production-chain emissions. Utilization of ST as feedstock produces the most GHG emissions in all cases.

In NF, the supply of comminuted HR, EW, and ST to a plant produces, respectively, 37%, 20%, and 19% more emissions than in SF, when SCS changes are accounted for. The difference in GHG emissions between NF and SF is mostly due to the slower natural decay of forest biomass in NF. For example, the GHG emissions due to SCS changes on a 100-year TH are 5.9 $gCO_2eq\ MJ^{-1}$ in SF for HR, while the corresponding figure in NF is 8.8 $gCO_2eq\ MJ^{-1}$. Also, GHG emissions due to transportation, forwarding, and forest operations are higher in NF, due to poorer availability of biomass and a less dense road network, but their effect on the total GHG emissions is minor when compared to the effect of SCS changes.

In the case of stumps, it should be noted that mineral soil clinging to the roots can further decrease the heating value by

approximately 20% [121]. However, the effect of soil material on supply-chain emissions is low, since cargo volume rather than weight is the limiting factor in the transportation, but impurities may prevent the use of stumps as feedstock in, for example, the pyrolysis process, in which feedstock-purity requirements are generally higher than in systems such as fluidized-bed combustion [122].

If SCS changes and storage emissions are disregarded, all bioenergy systems considered here satisfy the EU′s current (35%) and future (60% in 2018) GHG reduction requirements. Furthermore, even if the SCS changes are taken into account, the current 35% requirement is fulfilled by all the CHP systems and also in the case of pyrolysis oil used in heating. Meeting of the future 60% reduction requirement, however, is not guaranteed for all bioenergy schemes examined in the present study. This is especially true for torrefied pellets in CHP and pyrolysis oil in heating, if ST or EW is used as the feedstock. It should be noted that, if six-month storage emissions are fully accounted for, none of the bioenergy systems considered seem to achieve the 60% reduction requirement.

Regarding GHG emissions due to SCS changes, the estimated decay rates of forest biomass vary considerably between different studies Table 3. The decay rates depend on characteristics of decay models used and on input variables such as (but not limited to) temperature, precipitation, particle size and chemical composition of biomass [62,71,72,29,27,74,76,77]. In addition to the estimated decay rates, the relative GHG emissions for a given TH due to collection and energy use of forest biomass depend also on the calculation approach used. In this paper, the results are calculated for single-event combustion for a 100-year TH. The same approach is used in the US in the Massachusetts Renewable Energy Portfolio Standard (RPS) for forest residues [123], which, as far as the authors of this paper are aware, is the only legislation currently in force anywhere that addresses the issue of SCS changes due to forest residue collection and energy use.[1] In Europe, the possibility of inclusion of SCS changes in the EU sustainability criteria, and the related calculation procedures, is being discussed. Sensitivity analysis (Fig. 9) shows that the GHG savings achieved, if any, depend greatly on the SCS changes.

The most significant uncertainty, though, is related to the emissions of biomass storage. Literature and data regarding GHG emissions (CH_4 and N_2O) of comminuted forest biomass stockpiles are scarce. Furthermore, several case-dependent parameters influence the emissions; among these are ambient temperature, precipitation, the size of the stockpile, particle sizes, the rate of oxidation of CH_4 into CO_2 in the top layer of the stockpile, storage time, and compaction rate [64–67]. Even though prolonged storage leads to material and energy losses and, therefore, is not economically feasible in general, buffer storages of comminuted biomass are still in some cases required to guarantee security of supply. The duration of storage for comminuted forest biomass before combustion or conversion is, however, in most cases significantly shorter (up to few weeks) than the duration of storage for uncomminuted biomass at stands or roadside landings, during which the feedstock dries (a few months up to 1–2 years). For this reason, we included the storage emissions only as optional emissions and with a wide emission range. Any emissions due to material loss during storage of uncomminuted biomass can be judged to be negligible when compared to possible emissions stemming from the storage of comminuted biomass [124–126]; therefore, the former were not accounted for in this paper. It is clear that further research is needed, to quantify with more accuracy the GHG emissions of biomass storage, and also to investigate how these emissions could be avoided through, for example, logistical arrangements.

In this paper, the GHG emissions were assessed on a 100-year TH, because this is the TH applied in the underpinnings of international and EU climate-change policies. On the other hand, the renewable-energy targets of the EU and UNFCCC are fixed to year 2020 [3] and [127]. In view of this, a 100-year TH may be considered too long, as discussed in e.g., [128]. With a shorter TH, the climate impact of SCS changes would appear greater. For example, on a 20-year TH, the emissions due to SCS changes would be roughly 2–4 times greater than on a 100-year TH [62]. Also, if the TH is shortened to, for instance, 20 years, the GWP factors of other GHGs emitted should be adjusted accordingly. On a 20-year TH, the GWPs of CH_4 and N_2O would be 72 and 289, respectively, instead of 25 and 298[2] [16]. Where the bioenergy schemes considered in this paper are concerned, this would affect the emissions of storage most, since these consist primarily of CH_4 and N_2O.

The results of the study indicate that the possibilities for the greatest GHG emission reductions through the use of forest biomass in Finland are to be found in: (1) Minimizing emissions from storage by keeping the storage time of comminuted biomass short enough for the decay processes not to begin, (2) Utilizing HR, EW, and ST as feedstock, in that order, to minimize emissions due to SCS changes, and (3) Utilizing the feedstock without further conversion to replace peat in CHP production, or gasifying the feedstock to replace coal in CHP production.

[1] It should be noted that in the Massachusetts RPS, the TH is 20 years, during which 50% GHG savings must be achieved relative to a fossil comparator value. Also, GHG calculation for EW differs from that for forest residues, and energy use of stumps is not approved.

[2] The IPPC GWPs (CH_4 25, N_2O 298) [16] differ slightly from the ones used in the EU RED (CH_4 23, N_2O 296) [3]. The calculations in this paper are based on the EU RED GWPs.

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